

A UNIFIED ANALYSIS OF CONVERTERS WITH RESONANT SWITCHES

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ABSTRACT

Quasi-resonant converters are a recently introduced family of single-switch resonant converters featuring zero-current or zero-voltage switching. Recognition of the topological structure uniting these converters—and the PWM converters on which they are based—leads to general models of their dc and low-frequency ac behavior. An expression is derived that yields the dc conversion ratio of a quasi-resonant converter in terms of the well-known conversion ratio of the underlying PWM topology. A small-signal, low-frequency dynamic model is developed whose parameters also incorporate the PWM conversion ratio. The dc and ac models reveal that any quasi-resonant converter with a full-wave resonant switch has dc and low-frequency behavior identical to that of its PWM parent, with switching frequency control replacing duty ratio control. Converters with half-wave resonant switches act more like PWM converters under current programming or discontinuous conduction mode, exhibiting lossless damping in the small-signal model and output resistance at dc.

1 Introduction

The constant demand for smaller and lighter power converters is inexorably pushing switching frequencies higher and higher. Frequencies well into the megahertz range are currently found in commercial power supplies, while experimental converters switch even faster. Such high switching frequencies are made possible by *resonant topologies*. In contrast to the sharp-edged, quasi-rectangular switching waveforms of PWM converters, resonant converter topologies feature smooth, quasi-sinusoidal waveforms. These smooth waveforms bring the benefits of reduced switching losses, less interference, and insensitivity to dangerous parasitics.

Resonant converters have been known and used for decades, but recent developments contain some fundamentally different features. In particular, the family of dc-dc converters with resonant switches, known as *quasi-resonant* converters [3,4,5,6] is a departure from previous circuits [1,2]. The most striking feature of the new converters is the wide variety of topologies available. A recent paper, for example, illustrated no less than 26

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different topologies [6]. While such a variety offers designers many choices, it also presents something of a problem—how to assimilate, understand, and analyze so many converter circuits.

The purpose of this paper is to recognize the common structure and features of converters with resonant switches, and to use these properties to develop general dc and small-signal models of quasi-resonant converters. An example in Section 2 will illustrate the operation and features of a quasi-resonant converter. A general approach to the analysis of these converters begins in Section 3 with a discussion of the switching process in PWM converters. Section 4 describes how a quasi-resonant converter is made by creating a resonant switch in a PWM converter. The topological rules governing the resonant switch are used to derive the waveforms common to every resonant switch. In Section 5, these common waveforms lead to an equation for the dc conversion ratio of any quasi-resonant converter, an expression which exposes the important differences between half- and full-wave switches. A low-frequency small-signal dynamic model for quasi-resonant converters is developed in Section 6. Both the dc and ac models are extended to zero-voltage-switching resonant converters in Section 7 by application of duality principles. The small-signal model is verified in Section 8 by frequency response measurements of experimental resonant converters. Section 9 summarizes the properties of quasi-resonant converters revealed by these general methods of analysis.

2 Quasi-Resonant Converters

The resonant switch—a combination of switches and reactances producing quasi-sinusoidal waveforms—is responsible for the unusual properties of quasi-resonant converters. As an illustration of these properties, a zero-current-switching buck converter is presented in Fig. 1, along with waveforms for the switch current i_S and diode voltage v_D . On the assumption that the output inductor has negligibly small ripple current, the converter operates as follows.

At the beginning of each cycle of the resonant switch, the transistor Q is off and the diode D_2 is on. When Q is turned on, current rises linearly in the transistor, with the di/dt limited by the resonant inductor L_r . The switch current rises until i_S meets the output inductor current I , at which time diode D_2 turns off and the resonant elements L_r and C_r form a resonant circuit. The circuit resonates until i_S falls to zero and is in-

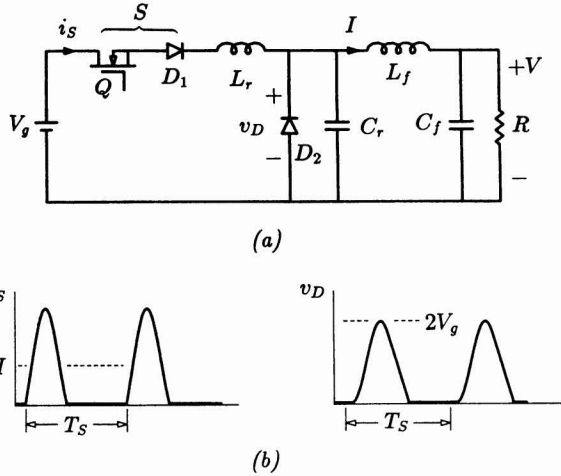


Figure 1: A quasi-resonant buck converter (a) and its switch waveforms (b).

interrupted by diode D_1 . The transistor is turned off while D_1 blocks. With Q and D_1 off the current I discharges C_r until the capacitor voltage falls to zero, turning on D_2 . The state of the circuit is now the same as initially, and the converter idles in this condition until the control circuit turns on Q to begin another cycle. The output voltage is controlled by varying the switching frequency and hence controlling how often the “pulses” of voltage in v_D appear across the output filter formed by L_f and C_f .

While only one of many quasi-resonant topologies, the converter of Fig. 1 illustrates the important features of a resonant switch and its effects in a power converter. First, the circuit of Fig. 1(a) is obviously a derivative of the common PWM buck topology shown in Fig. 2, differing only by the presence of the three components D_1 , L_r , and C_r . The visual similarity is no coincidence: quasi-resonant converters are all derived by addition of these three components to a PWM converter topology.

The waveforms of Fig. 1(b) demonstrate a second feature of the resonant switch: the transistor switch turns both on and off into zero current, allowing the converter to operate at very high frequencies without excessive switching losses. Just as important as low-loss switching is the fact that the waveforms of Fig. 1(b) have finite slopes. Such waveforms may cause less interference problems than the waveforms of (ideally) infinite slope found in PWM converters. Another consequence of the continuous waveforms of Fig. 1(b) is that parasitic inductances and capacitances can occur at several places in the converter without qualitatively affecting the waveforms. In some topologies, in fact, unavoidable parasitics (such as transformer leakage inductance) can be used as part or whole of the resonant

reactances L_r or C_r . This is a major advantage over PWM converters, in which parasitics can produce dangerous stresses and preclude very high switching frequencies.

A third feature of the resonant switch is that the current in L_r and voltage on C_r do not resonate continuously. Instead, they assume fixed values at the end of every cycle. This constraint considerably simplifies the analysis and control of quasi-resonant converters compared to converters that “ring” continuously.

Converters with resonant switches must be controlled by varying the switching frequency. This is apparent from the waveforms of Fig. 1(b), which show that while the turn-on of transistor Q is a matter of choice, the turn-off of D_1 is determined solely by the resonant current waveform and cannot be directly controlled.

The resonant buck converter of Fig. 1 is only one of many possible quasi-resonant converters. Any PWM topology—boost or flyback, for example—may be used instead of the buck as the PWM topology underlying the resonant converter. The two-quadrant switch consisting of Q and D_1 may be “half-wave” or “full-wave” [4]. Duality can be applied to the converter to yield a circuit which has its transistor switching at zero voltage instead of zero current [5]. Finally, in any particular topology, the resonant reactances L_r and C_r can be placed in several different positions while preserving the benefits of resonant switching [6].

3 PWM Switching

The term “PWM” (pulse-width modulation) is used here not to indicate any particular control scheme, but rather as a means of distinguishing converters with quasi-rectangular waveforms. For the present purposes, a PWM converter is defined as a dc-dc converter with one transistor, one diode, no losses, and small ripple in every reactance and the load, R . All reactances are linear. No magnetic coupling is allowed, but this restriction and the limitation to a single switch can be removed for some PWM converters—and for resonant converters derived from them—by fairly simple modifications to the analysis that follows.

From this definition of a PWM converter, one may prove the following two results [7].

Theorem 1 *The transistor Q , the diode D_2 , and a set of capacitors with total voltage V_{off} form a loop. The source V_g may also be included in the loop, with its voltage included in V_{off} .*

Theorem 2 *The transistor Q , the diode D_2 , and a set of inductors with total current I_{on} form a cut-set.*

The quantities V_{off} and I_{on} are easy to find in any particular topology: they are simply the voltage and current stresses on the transistor and diode. For example, in the buck converter of Fig. 2, V_{off} is the source voltage V_g , while I_{on} is the current I in the output filter inductor.

Application of Kirchhoff’s laws to the loop and cut-set of Theorems 1 and 2 gives

$$v_Q + v_D = V_{\text{off}} \quad (1)$$

$$i_Q + i_D = I_{\text{on}} \quad (2)$$

For efficient power conversion, the transistor and diode must operate in the switched mode, i.e., each device must be either on, with zero voltage (ideally), or off, with zero current. This

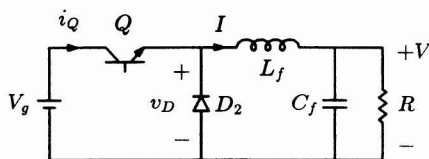


Figure 2: A PWM buck converter.

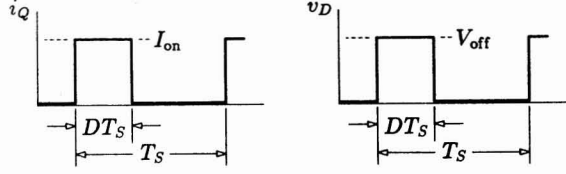


Figure 3: The transistor current and diode voltage waveforms in any PWM converter.

fact, together with Eqs.(1) and (2), implies that either the transistor or diode, but not both, must be on at any given time. The duty ratio D is defined as the fraction of a switching period in which the transistor is on. The waveforms for the transistor current and diode voltage in any PWM converter will be those of Fig. 3, to the extent that ripple can be neglected.

4 Resonant Switches

A quasi-resonant converter is the result of implementing a *resonant switch* in a PWM converter. The process involves adding three components to the PWM converter, according to certain topological rules. First, a diode D_1 is added either in series or in parallel with the transistor Q , forming a two-quadrant switch S . The resonant inductance L_r and capacitance C_r are then added.

The desired quasi-sinusoidal waveforms will appear only if L_r and C_r are inserted at certain locations in the PWM topology. A recent paper gave three rules governing the many possible locations [6]. Only two rules are necessary, however. The following two generate all *zero-current-switching* quasi-resonant topologies, i.e., those in which the transistor turns both on and off into zero current. (Zero-voltage-switching topologies are discussed in Section 7).

Rule 1 The resonant capacitor C_r must form a loop with the diode D_2 and a (possibly empty) set of “stiff” capacitors and voltage sources.

Rule 2 The resonant inductor L_r must form a cut-set with the two quadrant switch S and a (possibly empty) set of “stiff” inductors.

A “stiff” capacitor or inductor is one with small switching ripple. All non-resonant capacitors and inductors are assumed stiff, as in the original PWM converter. As pointed out in [6], Rule 1 ensures that the diode voltage will be continuous. Rule 2 (not found in [6]) similarly imposes continuity on the transistor current.

Two further results may be derived from Rules 1 and 2, relating the topology of the resonant switch to that of the original PWM converter [7]:

Theorem 3 The elements S , D_2 , L_r , and the elements producing the voltage V_{off} together form a loop.

Theorem 4 The elements S , D_2 , C_r , and the inductors producing I_{on} together form a cut-set.

These two results imply that L_r is inserted in *series* with elements of the PWM converter, while C_r is added in *parallel*

with the PWM elements to form a resonant switch. Theorems 3 and 4 hold for both zero-current and zero-voltage-switching converters.

Figure 1(a) verifies that these topological restrictions are satisfied for the resonant buck converter. The loop of Rule 1 contains only C_r and D_2 and the cut-set of Rule 2 contains only L_r and S . The loop of Theorem 3 contains S , D_2 , L_r , and the source V_g as V_{off} . The cut-set of Theorem 4 contains S , D_2 , C_r , and the filter inductor which carries the current I_{on} .

Define i_S , i_D , i_C , and i_L as the currents in the switch S , diode D_2 , capacitor C_r , and inductor L_r , respectively. Similarly define v_S , v_D , v_C , and v_L as the voltages across these elements. Application of Kirchhoff’s laws to Rules 1 and 2 and to Theorems 3 and 4 yields the following equations describing a resonant switch.

$$v_D - v_C = V_{dc} \quad (3)$$

$$i_S - i_L = I_{dc} \quad (4)$$

$$v_S + v_D + v_L = V_{off} \quad (5)$$

$$i_S + i_D - i_C = I_{on}, \quad (6)$$

where the small-ripple quantities V_{dc} and I_{dc} are generated by the (possibly empty) sets of “stiff” elements in Theorems 3 and 4. Both these sets are empty for the example of Fig. 1, so that V_{dc} and I_{dc} are both zero for this converter.

Although V_{dc} and I_{dc} will depend upon the location of L_r and C_r within a given topology, the actual values are of no concern here. What is important is that the quantities on the right-hand sides of Eqs.(3) through (6) are all dc, given the assumption of small ripple in all reactances but L_r and C_r .

These four equations are sufficient to derive the waveforms $i_S(t)$ and $v_D(t)$ for any zero-current resonant switch. To avoid losses, either i_D or v_D must be zero at any time, depending on whether the diode is on or off. Likewise, either i_S or v_S must be zero. Application of these dichotomies to Eqs.(3) through (6) produces the four states of the resonant switch shown in Table 1. The equations describing the waveforms i_S and v_D during each interval are given in Table 2, which uses the following definitions:

$$\omega_0 \equiv \frac{1}{\sqrt{L_r C_r}} \quad (7)$$

$$R_0 \equiv \sqrt{L_r / C_r} \quad (8)$$

$$\rho \equiv \frac{R_0 I_{on}}{V_{off}}. \quad (9)$$

The frequency $F_0 = \omega_0 / 2\pi$ is the resonant frequency and R_0 the characteristic resistance of the resonant tank formed by L_r and C_r during the resonant interval. The operating point of the resonant switch is indicated by the dimensionless quantity ρ , a

Interval	Name	Switch State	
		S	D_2
Initial State	Idle	OFF	ON
$0 < t < T_1$	Charging	ON	ON
$T_1 < t < T_2$	Resonant	ON	OFF
$T_2 < t < T_3$	Discharging	OFF	OFF
$T_3 < t < T_S$	Idle	OFF	ON

Table 1: The resonant switch takes on four different states during each switching period.

Interval	Switch Current $i_S(t)/I_{on}$	Diode Voltage $v_D(t)/V_{off}$	Duration $\omega_0 \Delta t$
Charging	$\frac{1}{\rho}\theta$	0	ρ
Resonant	$1 + \frac{1}{\rho} \sin \theta$	$1 - \cos \theta$	$\begin{cases} \pi + \sin^{-1} \rho & \text{(half-wave)} \\ 2\pi - \sin^{-1} \rho & \text{(full-wave)} \end{cases}$
Discharging			
half-wave:	0	$1 + \sqrt{1 - \rho^2} - \rho\theta$	$\frac{1}{\rho} \left(1 + \sqrt{1 - \rho^2} \right)$
full-wave:	0	$1 - \sqrt{1 - \rho^2} - \rho\theta$	$\frac{1}{\rho} \left(1 - \sqrt{1 - \rho^2} \right)$
Idle	0	0	—

Table 2: Summary of the equations describing the behavior of the zero-current resonant switch. The quantity θ is the product of ω_0 and the time elapsed since the beginning of an interval.

factor somewhat akin to the quality factor of a series resonant circuit.

The waveforms i_S and v_D are shown in Fig. 4 for half-wave and full-wave switches. The half-wave switch interrupts the current i_S when it first reaches zero, whereas the full-wave switch allows the current i_S to go negative. In the full-wave switch, the transistor is turned off while D_1 is conducting, so that the current i_S is stopped when it reaches zero from below. If $\rho > 1$ for either kind of switch, the current i_S never returns to zero and the switch S cannot turn off into zero current. Operation of the resonant switch therefore requires that $\rho \leq 1$. For the mode of operation shown in Fig. 4 and assumed throughout this paper, the voltage v_D must reset to zero before Q is turned on to begin the next cycle. This restriction limits the maximum switching frequency of the resonant switch.

It is important to note that the equations of Table 2 are independent of V_{dc} and I_{dc} of Eqs.(3) and (4). The waveforms i_S

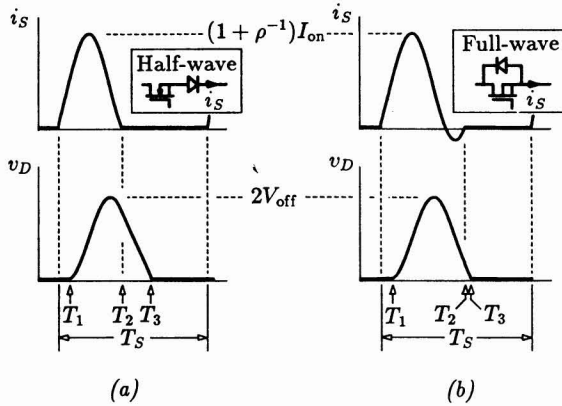


Figure 4: Switching waveforms in a quasi-resonant converter: half-wave (a), and full-wave (b). The upper curves show the current in the two-quadrant switch S (shown in the insets), and the lower curves are the voltage across the diode D_2 .

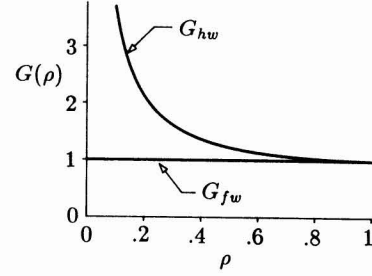


Figure 5: Plots of the functions G_{hw} and G_{fw} of Eqs.(12) and (13).

and v_D are therefore *independent* of the location of the resonant reactances within a topology.

While the equations of Table 2 are included for completeness, the only quantities needed in the following analysis are the averages of i_S and v_D over a single cycle. These are given by

$$\bar{i}_S = I_{on} \frac{F_S}{F_0} G(\rho) \quad (10)$$

$$\bar{v}_D = V_{off} \frac{F_S}{F_0} G(\rho) \quad (11)$$

where $F_S = 1/T_S$ is the switching frequency, and the function G depends on the type of switch S . If G_{hw} and G_{fw} denote the functions appropriate for the half-wave and full-wave switches, respectively, these functions are given by

$$G_{hw}(\rho) = \frac{1}{2\pi} \left[\frac{\rho}{2} + \pi + \sin^{-1} \rho + \frac{1}{\rho} \left(1 + \sqrt{1 - \rho^2} \right) \right] \quad (12)$$

$$G_{fw}(\rho) = \frac{1}{2\pi} \left[\frac{\rho}{2} + 2\pi - \sin^{-1} \rho + \frac{1}{\rho} \left(1 - \sqrt{1 - \rho^2} \right) \right] \quad (13)$$

The two functions are plotted in Fig. 5, revealing a striking difference between the half-wave and full-wave switches. The function G_{fw} is virtually independent of ρ , so that the averages \bar{i}_S/I_{on} and \bar{v}_D/V_{off} are functions of frequency alone, independent of the converter load. In contrast, G_{hw} depends heavily on ρ . The large difference in G_{hw} and G_{fw} is somewhat surprising given the similarities of the waveforms in Fig. 4, but the difference is real and has important consequences in the dc and small-signal ac behavior of quasi-resonant converters.

A resonant switch is not limited to a single inductance L_r or capacitance C_r . So long as each resonant reactance individually satisfies Rules 1 or 2, any number of resonant inductors and capacitors can be added to a PWM topology, resulting in a quasi-resonant converter with effective values of L_r and C_r equal to the sum of all the resonant inductances and capacitances, respectively. Quasi-resonant topologies are therefore *insensitive* to any parasitic reactances that appear in positions satisfying Rules 1 or 2. The only effect of such parasitics is to modify the values of L_r and C_r . The waveforms of the converter are qualitatively unchanged, and all the advantages of resonant switching remain in effect.

5 Dc Analysis

The average behavior of the resonant switch is used in this section to find the dc conversion ratio of any zero-current quasi-

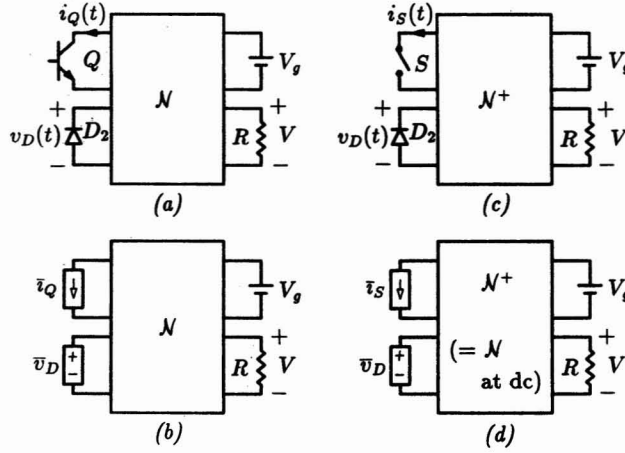


Figure 6: A PWM converter (a) and a dc equivalent circuit (b); a quasi-resonant converter (c) and a dc equivalent circuit (d).

resonant converter in terms of the conversion ratio of its PWM parent.

5.1 The Dc Conversion Ratio

Consider the diagram of Fig. 6(a) which views a PWM converter as a linear, time-invariant network N connected to the time-varying devices Q and D_2 . The network N has three inputs— V_g , the current $i_Q(t)$ and the voltage $v_D(t)$ —and a single output V , the voltage across the load. The dc conversion ratio of the PWM converter is defined as $M \equiv V/V_g$.

Since the network N is linear, the average of its output can be found by driving the network with only the averages of its inputs. Specifically, the conversion ratio M is unchanged if Q and D_2 are replaced with sources generating the averages of i_Q and v_D , as shown in Fig. 6(b). These average values are easily found from the waveforms of Fig. 3:

$$\bar{i}_Q = DI_{on} \quad (14)$$

$$\bar{v}_D = DV_{off} \quad (15)$$

The conversion ratio M of a PWM converter is known to be a function only of the duty ratio D . Let $M_P(D)$ denote this function so that

$$M = M_P(D) \quad (16)$$

for a PWM converter. The functions M_P are well-known for common PWM topologies. For example, $M_P(D)$ is D for a buck topology, $1/(1-D)$ for the boost, and $D/(1-D)$ for the buck-boost and Čuk topologies.

Figure 6(c) shows a quasi-resonant converter generated from the PWM converter of Fig. 6(a). The linear network N^+ of the quasi-resonant converter is the same as the PWM network N with the exception of the addition of L_r in series and C_r in parallel with the elements of N . At dc, however, the networks N and N^+ are equivalent, because L_r supports no average voltage and C_r carries no average current.

The conversion ratio of the resonant converter is unchanged by replacing the switch S and diode D_2 with sources producing the averages \bar{i}_S and \bar{v}_D , as shown in Fig. 6(d). The averages \bar{i}_S and \bar{v}_D are given by Eqs.(10) and (11).

Since there is no difference at dc between Figs. 6(b) and 6(d), a quasi-resonant converter and its PWM parent must have the same conversion ratio M whenever the averages \bar{i}_S (or \bar{i}_Q) and \bar{v}_D are the same in the two converters. Equations (10), (11), (14), and (15) reveal that this is so whenever

$$D = \frac{F_S}{F_0} G(\rho) \quad (17)$$

Use of Eq.(17) to replace D in Eq.(16) gives an expression for the conversion ratio of the resonant converter,

$$M = M_P \left(\frac{F_S}{F_0} G(\rho) \right) \quad (18)$$

This equation is not immediately useful, however, because ρ involves the ratio of I_{on} and V_{off} , which in turn depends on the conversion ratio. A relation between ρ and M will solve this problem. For every PWM converter, as defined in Section 3, (see, for example, [10] for a catalog of many such converters), the following is true:

$$\frac{V_{off}}{I_{on}} = \frac{R}{M} \quad (19)$$

where R is the ratio of dc load voltage and current. Use of this expression in Eq.(9), the definition of ρ , gives

$$\rho = \frac{R_0 I_{on}}{V_{off}} = M \frac{R_0}{R} \quad (20)$$

Substitution of Eq.(20) in Eq.(18) and solution for F_S/F_0 yields

$$\frac{F_S}{F_0} = \frac{D_P(M)}{G(MR_0/R)} \quad (21)$$

where $D_P(M)$ is the inverse of the PWM conversion-ratio function $M_P(D)$. For example, in the buck-boost converter, the conversion ratio is $M_P(D) = D/(1-D)$, and the inverse relation is $D_P(M) = M/(1+M)$. For a buck converter $M_P(D) = D$, so that $D_P(M)$ is simply M .

Equation (21) enables one to find the conversion ratio of any zero-current-switching resonant-switch converter knowing only the quantities R , R_0 , and the well-known PWM conversion function $M_P(D)$. (Section 7 shows how Eq.(21) is modified for zero-voltage converters.) The presence of the PWM function $D_P(M)$ in Eq.(21) highlights the fact that a PWM topology underlies each resonant-switch converter.

For the quasi-resonant buck converter of Fig. 1, the function $D_P(M)$ is simply M and the conversion ratio is governed by $F_S/F_0 = M/G(\frac{MR_0}{R})$. The conversion ratio of this converter is plotted in Fig. 7.

5.2 Implications of the Conversion Ratio

Half-wave and full-wave switches produce very different dc behavior, as the example of Fig. 7 shows. For a converter with a full-wave switch, the function G_{fw} is nearly unity for any permissible value of its argument, as shown in Fig. 5. With $G_{fw} = 1$, Eq.(18) becomes

$$M = M_P(F_S/F_0) \quad (22)$$

The conversion ratio of the resonant converter is found simply by replacing D with F_S/F_0 in the function M_P .

The conversion ratio of a full-wave converter will exhibit the same features as that of the PWM parent, including voltage step-up or step-down capabilities, linearity or nonlinearity

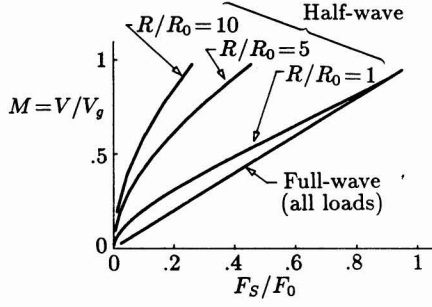


Figure 7: Dc conversion ratio of the quasi-resonant buck converter.

with respect to the control input, and a lack of load dependence. The curves of Fig. 7, for example, show that the full-wave buck converter has a conversion ratio less than 1, proportional to control (F_S/F_0), and independent of load, just like the PWM buck converter. Although insertion of a full-wave resonant switch in a PWM converter radically changes the converter's "internal" waveforms, the only "external" effect at dc is the replacement of the PWM control parameter D with the resonant control parameter F_S/F_0 . The same effect will be seen in half-wave converters as $\rho \rightarrow 1$, since G_{hw} and G_{fw} converge in that limit.

Half-wave resonant-switches have very different properties since the function G_{hw} depends heavily on ρ , as seen in Fig. 5. For example, the curves of Fig. 7 show that the conversion ratio of a half-wave buck converter is neither linear in control nor independent of load. A converter with a load-dependent conversion ratio has an *output resistance*, defined by the variation of output voltage with changing load current while the control input is held constant. Application of the definition of output resistance to Eq.(21) yields

$$R_{out} = \left[\frac{m D_P(M)}{M D'_P(M)} \right] R, \quad (23)$$

where D'_P is the derivative of D_P with respect to the argument M (note that D' is *not* $1 - D$), and m is defined by

$$m \equiv \rho \frac{|G'(\rho)|}{G(\rho)}. \quad (24)$$

For the half-wave switch, the derivative of G is

$$G'_{hw}(\rho) = -\frac{1}{4\pi} \left(\frac{1 + \sqrt{1 - \rho^2}}{\rho} \right)^2. \quad (25)$$

Figure 8 shows m for a half-wave resonant switch. For a full-wave resonant switch, G_{fw} is constant so that G' , m , and the output resistance are all zero.

For the half-wave buck converter of Fig. 1, $D_P(M)$ is simply M , and the output resistance is m times the dc load resistance R . At low values of ρ , the output resistance is substantial.

The output resistance introduced by a half-wave resonant switch is a "lossless" resistance, much like that produced by current programming and discontinuous conduction mode in PWM converters. The effect can be used to advantage when several converters are operated in parallel. The output resistances of half-wave resonant-switch converters will promote current-sharing when several converters are tied to the same load and operated with the same switching frequency.

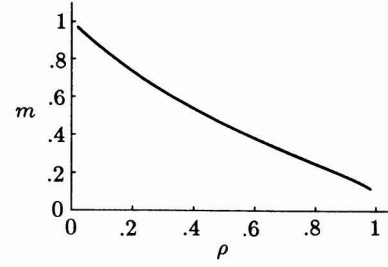


Figure 8: Plot of m as a function of ρ . The quantity m appears in expressions for the output resistance and in the small-signal parameters of Section 6.

6 Ac Analysis

The waveforms of the resonant switch violate the assumptions of most averaged ac models of PWM converters (such as state-space averaging [8]). The goal of this section is to develop a small-signal ac model of quasi-resonant converters that is valid for frequencies well below the switching frequency.

6.1 Equivalent Waveforms

With reference again to Fig. 6(c), a quasi-resonant converter can be viewed as the linear network \mathcal{N}^+ driven by the sources $i_S(t)$ and $v_D(t)$. When the resonant converter is modulated, I_{on} and V_{off} become the time-varying quantities $i_{on}(t)$ and $v_{off}(t)$. Modulation is assumed to occur only at frequencies well below the switching frequency, however, so that $i_{on}(t)$ and $v_{off}(t)$, as well as all the non-resonant states of the network \mathcal{N}^+ , vary slowly. (These quantities are already assumed to have small switching ripple.)

Only the low-frequency behavior of the network outputs are of interest, and hence only the low-frequency components of the inputs $i_S(t)$ and $v_D(t)$ are needed. Any two waveforms with the same low-frequency spectra as $i_S(t)$ and $v_D(t)$ can be applied to the ports of the network \mathcal{N}^+ without changing the low-frequency behavior of the network states and outputs.

It is postulated that the "averaged" waveforms

$$\bar{i}_S(t) = i_{on}(t) \frac{f_S(t)}{F_0} G [R_0 i_{on}(t)/v_{off}(t)] \quad (26)$$

$$\bar{v}_D(t) = v_{off}(t) \frac{f_S(t)}{F_0} G [R_0 i_{on}(t)/v_{off}(t)], \quad (27)$$

contain the same low-frequency information as the actual switching waveforms $i_S(t)$ and $v_D(t)$, where $f_S(t)$ is a continuous, low-frequency approximation of the switching frequency. This assumption can be justified using the approximations of small switching ripple and low-frequency modulation, provided $v_D(t)$ and $i_S(t)$ are sufficiently band-limited [7].

6.2 Small-Signal Model

The small-signal behavior of a quasi-resonant converter is found by linearizing Eqs.(26) and (27), the equivalent low-frequency waveforms replacing $i_S(t)$ and $v_D(t)$. Each equation is expanded as a function of the quantities \hat{i}_{on} , \hat{v}_{off} , and \hat{f}_S , where a hat ($\hat{\cdot}$) signifies the small-signal variation of a quantity. For

example, the variation of the switch current, \hat{i}_S , is given by

$$\hat{i}_S = \frac{\partial \bar{i}_S}{\partial i_{on}} \hat{i}_{on} + \frac{\partial \bar{i}_S}{\partial v_{off}} \hat{v}_{off} + \frac{\partial \bar{i}_S}{\partial f_S} \hat{f}_S, \quad (28)$$

with a similar expansion for \hat{v}_D . Expressions for the partial derivatives can be simplified considerably by use of Eq.(21) from Section 5 to eliminate the ratio F_S/F_0 . The parameter m , defined in Section 5 and plotted in Fig. 8, also can be used to advantage. Evaluation of the partial derivatives yields

$$h_{ii} \equiv \frac{\partial \bar{i}_S}{\partial I_{on}} = (1-m)D_P(M) \quad (29)$$

$$h_{iv} \equiv \frac{\partial \bar{i}_S}{\partial V_{off}} = \frac{mMD_P(M)}{R} \quad (30)$$

$$h_{if} \equiv \frac{\partial \bar{i}_S}{\partial F_S} = \frac{I_{on}D_P(M)}{F_S} \quad (31)$$

$$h_{vi} \equiv \frac{\partial \bar{v}_D}{\partial I_{on}} = -\frac{mRD_P(M)}{M} \quad (32)$$

$$h_{vv} \equiv \frac{\partial \bar{v}_D}{\partial V_{off}} = (1+m)D_P(M) \quad (33)$$

$$h_{vf} \equiv \frac{\partial \bar{v}_D}{\partial F_S} = \frac{V_{off}D_P(M)}{F_S} \quad (34)$$

The units of each h -parameter can be found by imagining a fraction bar (/) between the two subscripts. For instance, h_{vi} has units of v/i , or resistance. The function $D_P(M)$ is the inverse of the PWM conversion-ratio function, as described in Section 5.

A small-signal circuit model for a quasi-resonant converter is shown in Fig. 9. Each term of Eq.(28) is represented by a controlled current source of value given by the appropriate h -parameter. These three sources replace the switch S , while three voltage sources replace the diode D_2 . Frequency variation \hat{f}_S is considered an independent parameter, and the sources it controls are indicated by circles. Sources dependent upon voltages and currents elsewhere in the circuit are indicated by rectangles.

6.3 Interpretation of the Small-Signal Model

The small-signal model of Fig. 9 has several important features that are not readily apparent. As a means of exposing these

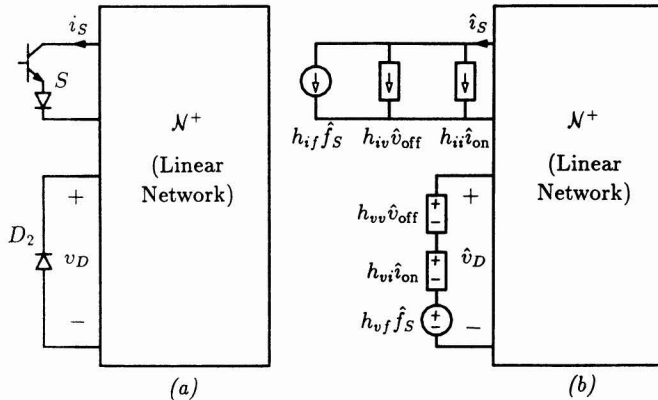


Figure 9: The small-signal model of a quasi-resonant converter is found by replacing the switch S and diode D_2 of the converter circuit (a) with controlled sources as in (b).

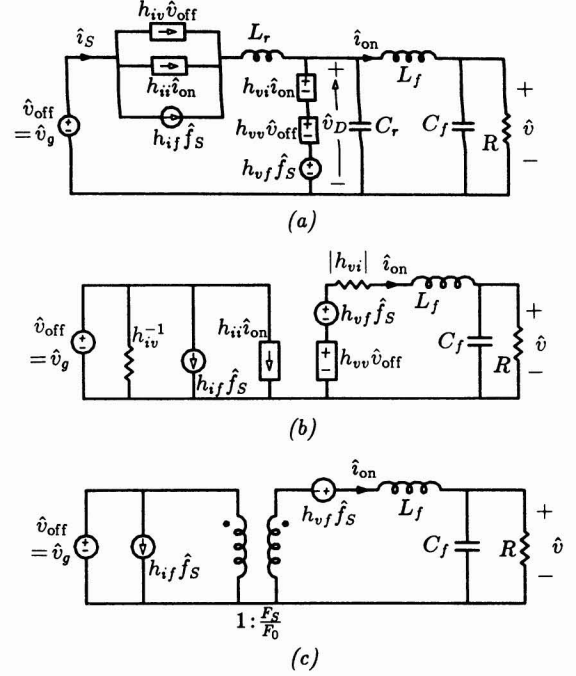


Figure 10: Small-signal circuit model of the quasi-resonant buck converter (a). Manipulation of the controlled sources leads to the equivalent circuit of (b). For a full-wave converter, the model further reduces to the circuit of (c).

features, Fig. 10 shows the small-signal circuit model of the resonant buck converter of Fig. 1(a). In Fig. 10(a), all voltages and currents have been replaced by their small-signal variations. Controlled sources take the place of the two-quadrant switch S and diode D_2 according to Fig. 9.

In Fig. 10(a), the resonant capacitor C_r appears across three ideal voltage sources, while L_r is in series with ideal current sources. Consequently, neither C_r nor L_r has any effect on the model and these elements may be removed. In particular, note that C_r and L_r do not increase the order of the small-signal model; they do not contribute state variables to the system.

This result is general. Rule 1 of Section 4 implies that, in any zero-current-switching quasi-resonant converter, C_r is in a loop of capacitors and voltage sources in the small-signal model. The voltage on C_r is therefore dependent on the states and inputs of the circuit model and cannot be a state variable. Rule 2 likewise puts L_r in a cut-set of inductors and current sources, making the current in L_r dependent. The order of the small-signal model for a quasi-resonant converter will therefore be the same as that of the state-space-averaged model [8] (or other low-frequency model) of the parent PWM converter.

Even though L_r and C_r do not increase the system order, under some conditions these elements can still appear in the small-signal circuit model. For instance, another possible location (satisfying Rule 1) for C_r in the buck topology is across the filter inductor L_f . In this position, C_r and L_f form an undamped parallel resonant circuit, inserting a "notch" in the converter's transfer functions. If L_f is large enough, the "notch" can appear at frequencies well below the switching frequency.

Even though the *order* of the circuit is not increased by the presence of C_r , the resonant capacitor can nevertheless have a significant effect on the response.

This somewhat unusual example demonstrates that one cannot summarily remove C_r and L_r from the small-signal circuit model. In most cases, however, L_r and C_r will have negligible effects on the response, either because of their topological position or because their values are so small that they have no effect at frequencies where the model is valid.

Removal of L_r and C_r from Fig. 10(a) and manipulation of the controlled sources leads to the equivalent circuit shown in Fig. 10(b). When the converter has a half-wave switch, as shown in Fig. 1(a), the resistances h_{iv}^{-1} and $|h_{vi}|$ of Fig. 10(b) are both positive, and the sources containing h_{ii} and h_{vv} cannot be combined into a transformer. The network is lossy and non-reciprocal. The presence of the resistors demonstrates an important result: half-wave converters have lossless damping of their transfer functions. The effect is much like that found in PWM converters with discontinuous conduction mode [9], current programming [12], or storage-time modulation [13]. No power is dissipated in the switches or reactances of the converter, but modulation of the switching instants tends to remove perturbations faster than in the “undamped” converter.

As $\rho \rightarrow 1$, the half-wave resonant-switch waveforms approach those of a full-wave converter. Both h_{iv} and h_{vi} approach zero and the damping disappears. If the converter is outfitted with a full-wave switch (D_1 anti-parallel to the transistor), $m = 0$ so that h_{vv} and h_{ii} are both equal to $D_P(M)$, which in turn equals F_S/F_0 for the full-wave converter. The sources containing h_{vv} and h_{ii} constitute an ideal transformer, as shown in the equivalent circuit of Fig. 10(c). With the equivalence of f_S/F_0 and d as control variables, the model of Fig. 10(c) agrees with the state-space-averaged model of the PWM buck converter [8].

This again is a general result. Full-wave converters, so long as L_r and C_r do not affect the response, have the same small-signal dynamics as their PWM parent converters. When f_S/F_0 and d are equated, the small-signal model suggested in Fig. 9 agrees with “averaged” models of the parent PWM converter [10,11]. To the extent that the small-ripple approximation is met, the state-space averaged model [8] is also equivalent.

7 Zero-Voltage Resonant Switches

The dual of a zero-current-switching resonant switch is a zero-voltage switch, a circuit that allows the switching transistor to turn both on and off into zero voltage. Zero-voltage switches can be studied by applying duality to the development of the zero-current switch, including the dc and ac models. The duality transformation imposes the changes listed in Table 3. Under these changes, Rules 1 and 2 become the following two rules defining allowable locations of the resonant reactances in a zero-voltage resonant converter:

Rule 3 The resonant inductor L_r must form a cut-set with the diode D_2 and a (possibly empty) set of “stiff” inductors.

Rule 4 The resonant capacitor C_r must form a loop with the two-quadrant switch S and a (possibly empty) set of “stiff” capacitors and voltage sources.

Theorems 3 and 4 are unchanged by duality. As with the zero-current converters, the reactances L_r and C_r have several possible positions within a given topology.

Zero-Current		Zero-Voltage
I_{on}	\rightarrow	V_{off}
V_{off}	\rightarrow	I_{on}
R_0	\rightarrow	R_0^{-1}
R	\rightarrow	R^{-1}
ρ	\rightarrow	ρ^{-1}
i_S	\rightarrow	v_S
v_D	\rightarrow	i_D
M	\rightarrow	M^{-1}
$D_P(M)$	\rightarrow	$1 - D_P(M)$

Table 3: Transformations that change the equations for a zero-current quasi-resonant converter into those for a zero-voltage converter.

The conversion ratio of a zero-voltage converter is given by

$$\frac{F_S}{F_0} = \frac{1 - D_P(M)}{G(R/MR_0)}. \quad (35)$$

Note that the function G is unchanged by the duality transformation. The small-signal model is illustrated in Fig. 11, and the parameters are given by

$$h_{vv} = [1 - D_P(M)](1 - m) \quad (36)$$

$$h_{vi} = \frac{mR[1 - D_P(M)]}{M} \quad (37)$$

$$h_{vf} = V_{off} \frac{[1 - D_P(M)]}{F_S} \quad (38)$$

$$h_{iv} = -\frac{mM[1 - D_P(M)]}{R} \quad (39)$$

$$h_{ii} = (1 + m)[1 - D_P(M)] \quad (40)$$

$$h_{if} = I_{on} \frac{[1 - D_P(M)]}{F_S} \quad (41)$$

As before, the ratio of the subscripts gives the dimensions of each parameter.

In a full-wave zero-voltage converter, $G(\rho^{-1})$ is nearly constant for all values $0 < \rho^{-1} < 1$, and $m = 0$. The dc and ac behavior of zero-voltage converters is therefore the same as their zero-current counterparts. The full-wave converter behaves like a PWM converter with $1 - D$ replaced by F_S/F_0 . In half-wave zero-voltage converters, G and m both depend heavily on ρ^{-1} . These converters will exhibit dc output resistance and damping in the small-signal model.

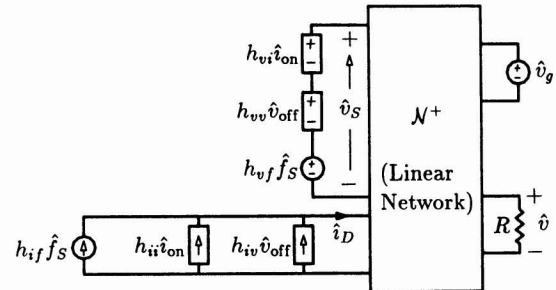
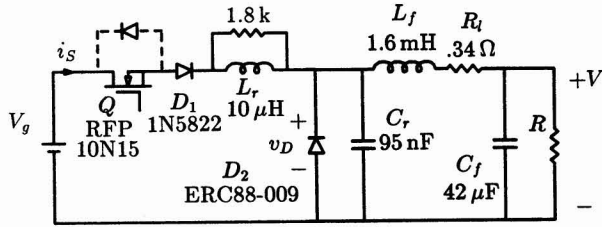


Figure 11: The small-signal model of a zero-voltage-switching converter. The switch S and diode D_2 have been replaced by controlled sources according to Eqs. (36) through (41).



L_f : 105 t #22 on TDK H7C4 PQ2625 core
 C_f : $4 \times 10 \mu F$, 100V, mylar
 L_r : 8 t #20 on TDK H7C1 RM6 core, $A_L = 160$
 C_r : $2 \times .047 \mu F$, 100V, polystyrene

Figure 12: Experimental resonant-switch buck converter.

8 Experimental Measurements

As a means of verifying the small-signal model developed in Section 6, two quasi-resonant converters were constructed and their control-to-output frequency responses measured. A VCO modulated the switching frequency while a network analyzer measured the response between the VCO input voltage and the converter output voltage. The VCO was modelled as a constant gain, a reasonable approximation for frequencies well below the switching frequency.

The first converter measured used the buck topology, as in the examples of Sections 2 and 6.3. The experimental converter is shown in Fig. 12. (The 1.8k resistor was added to damp ringing between the resonant inductance L_r and its parasitic capacitance when the switch S is open.)

Figure 13 shows the frequency response of this converter when a half-wave switch is used. The output filter alone has a Q of about 5.6, but the half-wave resonant switch introduces the resistance $|h_{vi}|$ in series with the inductor L_f . At the operating point of $\rho = 0.17$, $|h_{vi}|$ is about 0.8 times the load resistance, and the effective Q of the filter is reduced to only 0.21. The measured response clearly shows that the poles have become

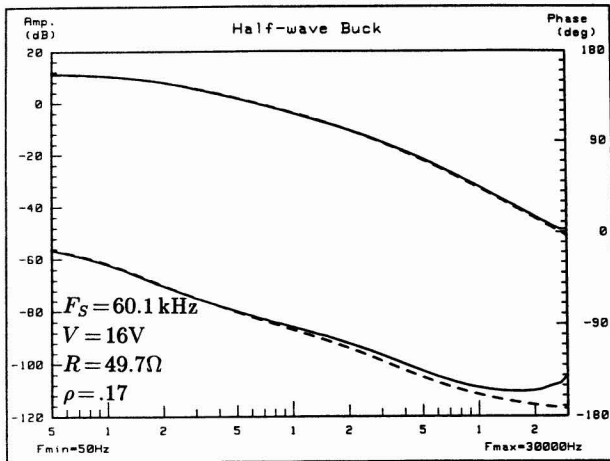


Figure 13: Measured (solid lines) and predicted (dashed lines) control-to-output frequency response of a half-wave buck converter.

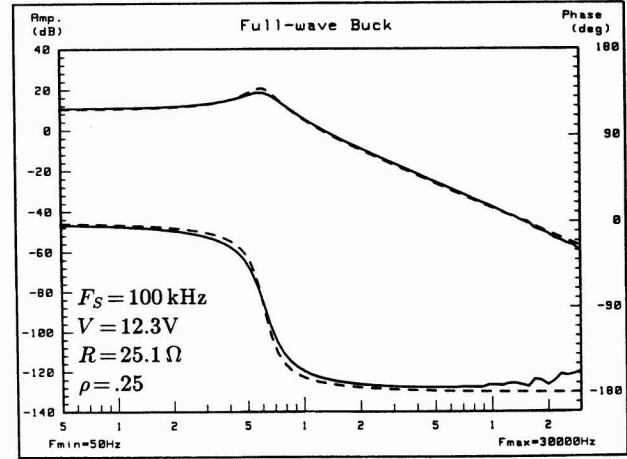


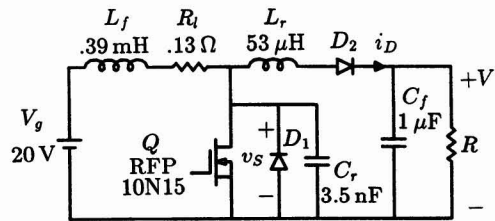
Figure 14: Measured (solid lines) and predicted (dashed lines) control-to-output response of a buck converter with a full-wave resonant switch.

real and well-separated as a result of this additional damping.

Figure 14 shows the response of the buck converter with a full-wave resonant switch (as indicated by the dashed-line position of D_1 in Fig. 12). The measured response exhibits the Q of the output filter alone, with almost no additional damping.

Both the half- and full-wave measurements show good agreement with the small-signal model of Section 6. The phase deviations at higher frequencies are likely a result of neglecting sampling effects in the VCO and converter.

A second converter, shown in Fig. 15, was built to verify the results of Section 7 for zero-voltage converters. The response of this boost converter with a half-wave switch appears in Fig. 16 and shows good agreement with the model of Section 7. Although the half-wave switch has introduced damping, the right-half-plane zero is still present. This will be the case for any operating point of the resonant boost converter.



L_f : 67 t #20 on 3019 pot core, 1.35mm gap
 C_f : $1.0 \mu F$, 100V, polypropylene
 L_r : 18 t #18 on TDK H7C1 RM6 core, $A_L = 160$
 C_r : $4 \times .001 \mu F$, 100V, polystyrene

D_1, D_2 : MUR830

Figure 15: Experimental zero-voltage-switching boost converter.

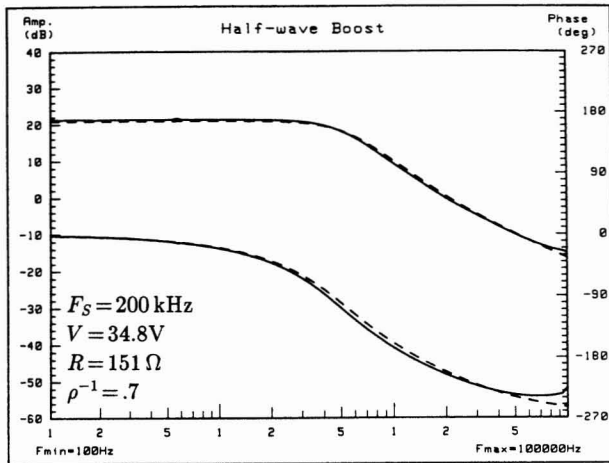


Figure 16: Measured (solid lines) and predicted (dashed lines) frequency response of the boost converter of Fig. 15.

9 Conclusions

Quasi-resonant converters possess a unique combination of features. With their quasi-sinusoidal waveforms, they have the desirable features of zero-current or zero-voltage switching and insensitivity to parasitics. The presence of an idle interval in the sequence of switched networks makes these converters easy to analyze, however, when compared to most other resonant converters.

Converters with resonant switches come in an astounding variety of topologies. The quasi-resonant converter is first of all based upon any one of many PWM topologies. To the basic PWM converter is added either a zero-voltage or a zero-current resonant switch. The switch can be either half-wave or full-wave, and the resonant reactances may appear in many different positions within the topology without changing the dc behavior.

By limiting consideration to a certain class of converters—those with single switches and no coupling—the topology and behavior of the original PWM converter can be applied to the quasi-resonant converter, yielding general expressions for the dc conversion ratio and small-signal coefficients. The dc behavior of any converter with a resonant switch is governed by Eq.(21) or (35) for zero-current or zero-voltage converters, respectively. These equations use the known conversion ratio of the underlying PWM converters. The parameters of the small-signal dynamic model use this same ratio, giving visible evidence of the role the underlying PWM converter plays in the behavior of the resonant converter.

The general analysis performed here revealed that the qualitative behavior of a quasi-resonant converter is determined mainly by the type of resonant switch used, full- or half-wave. A converter with a full-wave switch is similar to its PWM parent in every respect. The dc conversion ratio and ac small-signal behavior (to the extent that the resonant reactances may be neglected in the small-signal model) are both obtained by substitution of the resonant control variable f_s/F_0 for the duty ratio d which controls the PWM converter. Full-wave converters have load-independent conversion ratios and undamped dynamic responses. Half-wave converters, in contrast, demonstrate behav-

ior remarkably similar to PWM converters in the discontinuous conduction mode. The conversion ratio is load-dependent, producing a lossless output resistance that fosters current-sharing among paralleled converters. The half-wave switch also introduces lossless damping in the small-signal dynamic response.

The dc analysis of quasi-resonant converters relies on the assumptions of losslessness and of small ripple in the converter's non-resonant reactances, while the small-signal analysis makes the additional approximation that modulation occurs far below the switching frequency. The loss in accuracy caused by these approximations is rewarded by the benefits of generality and simplicity in the resulting models. The results given here are offered as a means of understanding how quasi-resonant converters behave and how the many variations relate to one another and to their PWM parents.

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